Opportunities of European Hydrogen Supply Potentials for Germany's Hydrogen Market

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***Abstract*— Germany's ambitious climate targets necessitate a fundamental transformation of the energy system. Green hydrogen plays a substantial role in replacing fossil fuels in sectors where electrification is either economically unviable or technically unfeasible. Europe offers substantial hydrogen potential, which could be utilized to meet Germany's demand. The development of the European hydrogen market requires a thorough understanding of supply and demand dynamics. This study presents a model-based approach to derive market wholesale prices for hydrogen based on different European import corridors. Hydrogen cost-potential curves are derived, revealing most cost-competitive locations in Southern Europe. Hydrogen wholesale prices range from 2.35 €/kg to 2.70 €/kg. While the lowest prices are identified for imports from the Southwest Corridor, the highest are observed for the North Sea Corridor. A pan-European import reduces the wholesale price to 2.30 €/kg, covering an annual hydrogen demand of 16 Mt/a, with a significant share of production in Spain.**

***Index Terms*—Energy system modeling, Hydrogen market modeling, Hydrogen prices, Hydrogen supply curves, European hydrogen trade**

Introduction

The European Commission has established a target of achieving climate neutrality by the year 2050, a goal that is in alignment with the objectives of the Green Deal [1]. This objective is to be achieved through a multisectoral strategy that involves the reduction of net greenhouse gas emissions and the transition towards a sustainable economy. Germany aims to achieve this goal by 2045, which requires a significant utilization of renewable energy potentials and the substitution of fossil fuels in areas where electrification is either not feasible or not economically viable. Green hydrogen and other electricity-based fuels play a crucial role in decarbonizing hard-to-abate sectors, serving as both a feedstock and an energy carrier in industries such as steel, cement, and heavy-duty transportation. However, a significant share is expected to be covered by imports due to limited domestic resources [2].

In the context of an emerging hydrogen market, Europe plays a strategic role in enhancing cost competitiveness and promoting energy security. Europe has substantial potential for green hydrogen production, which could contribute significantly to meeting Germany's hydrogen demand [3]. However, demand is highly influenced by market prices, reflecting the interplay between supply and demand dynamics, as demonstrated in [4]. The price sensitivity of hydrogen demand in the energy system varies across sectors and technologies, reflecting their unique economic and operational characteristics.

Various studies have examined the supply costs for green hydrogen using linear optimization models [5-7]. Additionally, the feasibility of hydrogen trade, including production costs and transportation via ships and pipelines, has been extensively examined in the literature [8-10]. However, these methods do not account for the dynamic interplay between supply and demand, a critical factor in the estimation of market prices.

The present study estimates hydrogen wholesale prices for various import routes to Germany for the year 2050. A linear optimization model is employed to generate regional cost-potential curves across Europe, providing a foundation for a detailed supply-side analysis. These curves are then aggregated into supply curves for different import corridors, incorporating transport costs to capture the spatial heterogeneity of production costs across Europe. Subsequently, a market model is introduced to derive hydrogen wholesale prices under the assumption of perfect competition, by incorporating supply and demand curves. The analysis compares various import routes with a pan-European import scenario, evaluating producer and consumer surplus across these trade pathways. As a result, the study identifies opportunities in the context of a European hydrogen market, providing valuable insights into the hydrogen economy for policymakers, industry stakeholders, and researchers.

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METHODOLOGY

This section provides a detailed description of the methodological approach employed to integrate hydrogen supply and demand curves for the assessment of hydrogen wholesale prices for different import routes to Germany. The geographic scope of this assessment covers the 27 EU Member States, the United Kingdom, Norway, Switzerland, and the Western Balkans, specifically Albania, Kosovo, Montenegro, North Macedonia, and Serbia. The spatial resolution is defined on the basis of the Nomenclature of Territorial Units for Statistics (NUTS) using the NUTS 3 level [11-13]. The objective of the supply analysis is to derive regional and national cost-potential curves for green hydrogen production for the target year 2050. This is done using a cost optimization model based on the ETHOS.FINE framework [14]. The objective of this optimization model is to minimize the total cost of the energy system while determining the optimal sizing and energy flows of its individual components. The components of the hydrogen energy system considered in this study are shown in Fig. 1. The off-grid energy system consists of renewable energy sources from onshore wind and ground-mounted photovoltaics. These are connected directly to a proton exchange membrane (PEM) electrolyzer with a constant conversion efficiency of $71\%_{LHV}$. A lithium-ion battery and a pressurized hydrogen gas storage system can be utilized to increase the flexibility of the overall system.

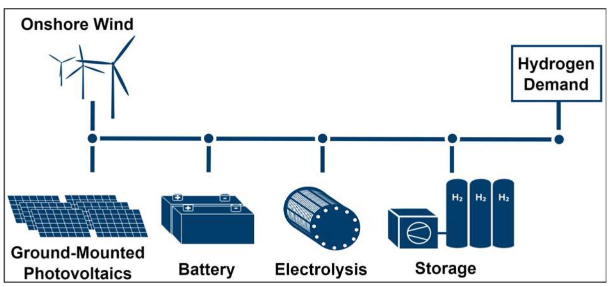

Fig. 1: Overview of the different components of the hydrogen energy system model.

The land eligibility assessment for ground-mounted photovoltaics and wind onshore is derived from [15-17], which consider several criteria including topography, land use, and sociopolitical factors. The identified areas serve as a basis for the evaluation of the potential of renewable energy for each NUTS 3 region in Europe. These are used for hourly-resolved simulations of energy production, on the basis of [15] and [18]. The time-series data is aggregated into 80 typical periods using the python based time series aggregation module (tsam) [19]. This approach enables a substantial reduction in computational time while maintaining a high model quality.

The described off-grid system is applied to each NUTS 3 region under consideration to derive regional cost-potential curves. Given the assumption of a direct connection between renewables and electrolysis, the configuration is consistent with the Renewable Energy Directive [20], thereby meeting the requirements of additionality, as well as temporal and geographical correlation. The energy system is optimized for multiple annual hydrogen production levels, with the objective of discretizing the cost-potential curve based on the approach

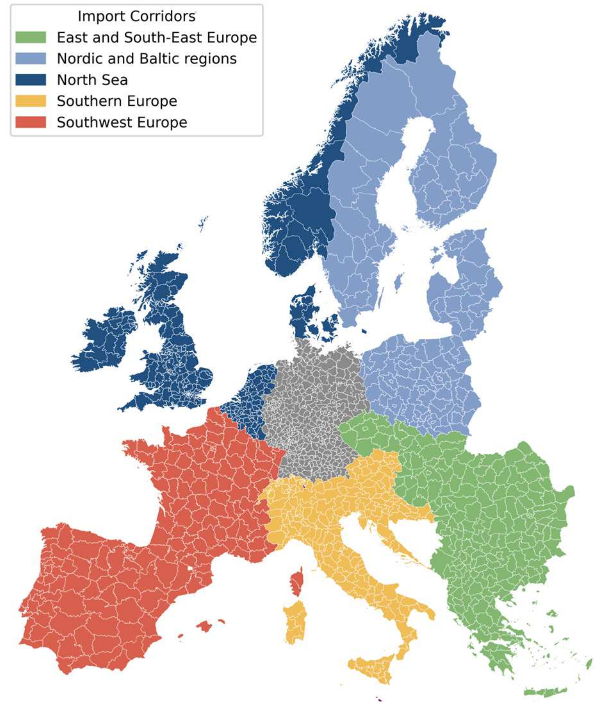

Fig. 2: Overview of the different hydrogen import corridors from Europe to Germany.

of [8]. These production levels are set at 5%, 25%, 50%, 75%, and 100% of the maximum regional hydrogen production potential, respectively. The hydrogen production costs for each production level are calculated based on the total annual energy system cost and the production quantity. This approach enables the formation of regionalized cost-potential curves. In a subsequent step, the regional cost-potential data is aggregated into import corridor clusters based on marginal costs. The applied clusters are shown in Fig. 2, which are in partially aligned with the import corridors defined in the European Hydrogen Backbone [21].

Given the focus of this study on Germany, it is assumed that hydrogen imports will be delivered to a single virtual trading hub, which serves as a central reference point within the country. The supply curves are subsequently adjusted to account for the national demand for electricity and hydrogen, as well as for transportation costs to the virtual trading hub. Following the approach of [17], supply curves are modified to prioritize national demand over exports. This is illustrated in Fig. 3 with an exemplary supply curve, where the quantity of the supply curve up to base-point 1 is allocated first for national electricity demand, followed by national hydrogen demand and finally export quantity. Base-point 1 is determined on a national level by first calculating the share of onshore wind and ground-mounted photovoltaics generation required to meet national electricity demand in 2050. Consequently, the quantity of the share is converted to a hydrogen equivalent by applying the conversion efficiency of the electrolyzer. Subsequently, base-point 2 is derived from the national hydrogen demand. The annual generation and demand data for electricity and hydrogen

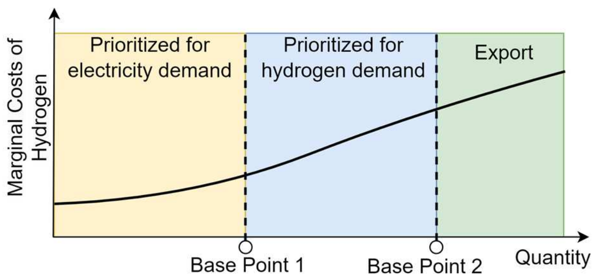

Fig. 4: Supply curve illustrating the prioritization of electricity demand, hydrogen demand, and export quantity, adapted from [17].

are based on the dataset provided by ENTSO-E and ENTSOG TYNDP 2024 scenarios [22].

For the transportation of green hydrogen within Europe transmission pipelines are assumed, according to the European Hydrogen Backbone initiative [23]. The transportation costs for newly built pipelines for the year 2050 are obtained from [24] as a function of the transport distance. The straight-line distance from each NUTS 3 region center to the virtual trading hub in Germany is calculated, applying a detour factor of 1.2. This adjusted distance is then used to derive the corresponding transportation cost and incorporated into the respective regional supply curves. The price-elastic hydrogen demand curve used in this study for Germany for the year 2045 is extracted from [4]. The supply and demand curves are utilized as an input for the hydrogen market model to analyze hydrogen wholesale prices for Germany for the defined import corridors, as illustrated in Fig. 4. This is achieved by determining the market-clearing price for 2050 at the intersection of the supply and demand curves, using a partial equilibrium approach. Assuming perfect competition, the determination of hydrogen wholesale prices is driven primarily by supply and demand dynamics. Potential interdependencies with other energy markets are neglected, thus isolating the effects within the hydrogen market for a single year.

RESULTS

The aggregated hydrogen cost-potential curves for the different import corridors, as well as for Germany, are shown in Fig. 5. An increase in cost with annual production quantity is observed for each cost-curve. As production quantity increases, less efficient renewable energy sources must be expanded, resulting in higher overall production costs. The marginal cost for Germany starts at 2.20 €/kg, followed by an increase to 3.50 €/kg at 500 TWh and 5 €/kg at 600 TWh.

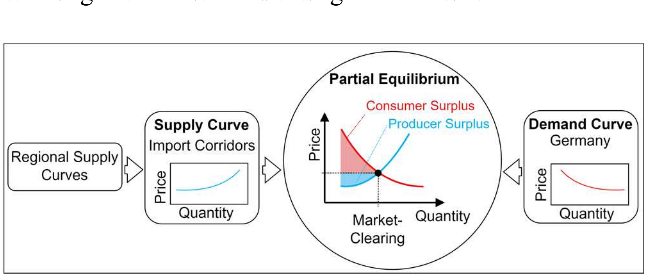

Fig. 5: Conceptual representation of the hydrogen market model based on supply and demand curves.

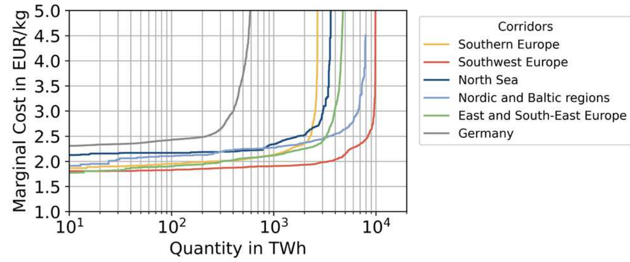

Fig. 3: Aggregated hydrogen supply curves for Germany and the different import corridors.

The overall costs remain higher than those of the import corridors, primarily due to the utilization of less efficient renewable energy sources. At a production quantity of 10 TWh, the cost for the North Sea Corridor is observed at 2.10 €/kg, while costs for the remaining corridors range between 1.75 and 1.90 €/kg. For a hydrogen quantity of 1000 TWh, the costs of the import corridors range between 1.90 and 2.30 €/kg, with the lowest cost observed in the Southwest as well as East and Southeast Corridor. Overall, the Southwest Corridor exhibits the highest potential, with a marginal cost increase between 10 and 2000 TWh. This is primarily attributed to the abundant availability of efficient ground-mounted photovoltaics potentials, which enables cost-effective scaling of hydrogen production. Consequently, the cost increase with production quantity remains comparatively lower than in other regions. It is evident that the import corridors reveal substantial potential in terms of reduced production costs for green hydrogen compared with domestic production in Germany.

As illustrated in Fig. 6, wholesale prices of hydrogen for Germany for the various import corridors are presented as a result of the hydrogen market model. In addition to the defined import corridors, a European scenario is shown, representing imports from all regions considered in this study. Within this scenario, a hydrogen wholesale price of 2.30 €/kg with a quantity of 16 Mt is observed. Additionally, the results reveal a producer surplus of 0.5 billion € and a consumer surplus of 5.8 billion €. The substantial consumer surplus indicates that market conditions are advantageous for consumers, while the comparatively smaller producer surplus suggests that profit margins for suppliers may be constrained under the assumed market conditions. A marginal increase in the wholesale price is observed for the Southwest Corridor compared to the European scenario. This is accompanied by a minor decrease in consumer surplus, while producer surplus is reduced by 26%. A subsequent increase in wholesale price is observed for the remaining import corridors. The North Sea Corridor has been identified as the most expensive, with a wholesale price of 2.70 €/kg. Notably, this import corridor leads to the most significant increase in producer surplus, rising by 48%, while consumer surplus decreases by 40% compared to the European scenario. This dynamic is driven by the widening margin between the market wholesale price, the consumers' willingness to pay, and the marginal supply price of producers. Overall, wholesale prices for the five import corridors range between 2.35 and 2.70 €/kg, with the lowest price identified in the Southwest Corridor and the highest in the North Sea Corridor. This observation underscores the cost advantages of hydrogen

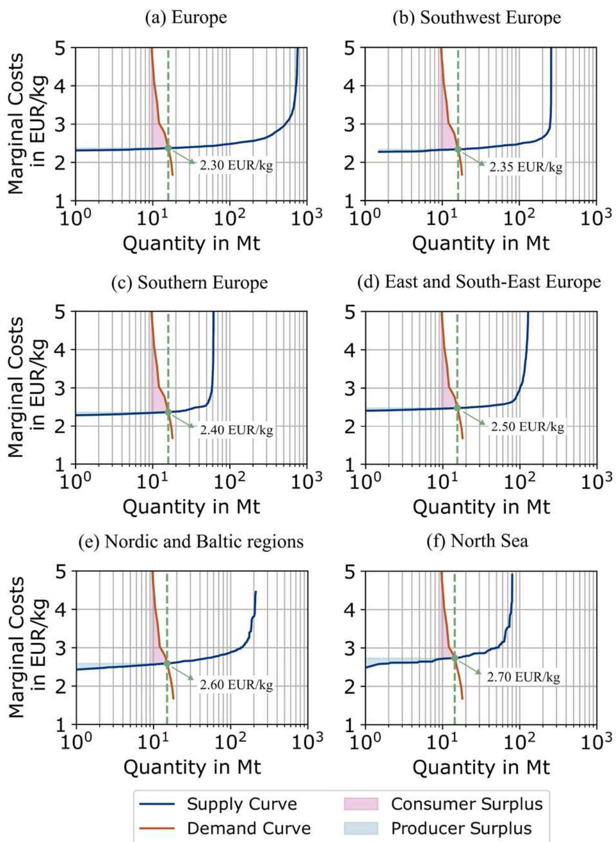

Fig. 6: Resulting hydrogen market wholesale prices, consumer surplus, and producer surplus for different import corridors supplying Germany.

import from Southern Europe, resulting in a significantly higher consumer surplus in Germany compared to other import corridors.

The corresponding exporting regions of different import scenarios are illustrated in Fig. 7. It is apparent that the European scenario is characterized by a concentration of importing regions in Southern Europe, with Spain leading in terms of production quantity, followed by France and Italy. The NUTS 3 region of Zaragoza, located in Spain, has been identified as the region with the highest annual production quantity, at approximately 3.4 Mt/a, thereby demonstrating the substantial upscaling of renewable photovoltaics potentials. The results from the Southwest Corridor, which exhibited a slight increase in hydrogen wholesale price compared to the European scenario, show a similar pattern in terms of the location of the exporting regions. Hydrogen production occurs in regions located in the northeast of Spain and several regions in the south of France, with approximately 88% of the annual production occurring in Spain. The North Sea Corridor is characterized by a substantial concentration of production in Norway, with 77% of annual production occurring in this region. The United Kingdom and Ireland follow closely behind, with 12% and 11% of annual production, respectively. Notably, the region of Trøndelag is a significant producer, with an annual output of approximately 4.5 Mt/a, driven by the utilization of favorable wind onshore potentials.

Conclusion

This study evaluates hydrogen wholesale prices, as a results of different import routes to Germany in 2050. Hydrogen supply and demand curves are incorporated into a partial equilibrium framework, allowing for the evaluation of the different import corridors based on hydrogen wholesale price, consumer surplus, and producer surplus.

The findings of this study reveal substantial regional cost variations across Europe. However, the most cost-effective production locations, as determined by production costs and quantity, are predominantly concentrated in Southern Europe. Consequently, imports from southern regions have the potential to reduce hydrogen wholesale prices to 2.30 €/kg, thereby offering a substantial benefit to consumers. This results in an approximate increase in consumer surplus to 5.8 billion €, as the annual hydrogen demand of 16 Mt/a is met. The findings indicate that the development of a European Hydrogen Market could offer significant economic benefits to Germany, as domestic hydrogen potentials are less competitive. Hydrogen wholesale prices obtained from the import corridors under consideration exhibit a variation of up to 15%. This finding indicates that while cost differences are present, there is some

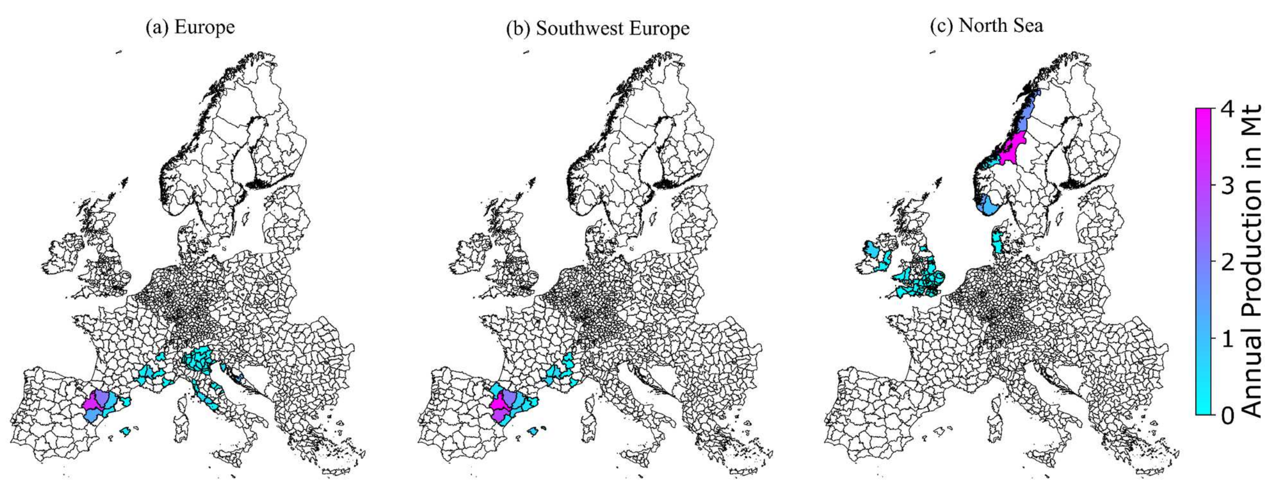

Fig. 7: Annual hydrogen production volumes for different import corridors to Germany: (a) Europe, (b) Southwest Europe, and (c) the North Sea.

flexibility in diversifying supply sources without necessarily leading to substantial increases in overall wholesale prices. This flexibility could support strategies aimed at enhancing energy security while maintaining cost competitiveness.

While this work provides valuable insights into potential hydrogen wholesale prices for Germany, it is necessary to emphasize that these are derived under the assumption of a perfectly competitive hydrogen market, neglecting potential market distortions, policy interventions, and interactions with other markets. Consequently, the results should not be interpreted as precise forecasts. Instead, they should be regarded as scenario-based assessments, given the inherent uncertainties involved. A primary source of uncertainty is associated with cost projections for future investments, which are subject to various factors, including technological advancements, policy frameworks and market conditions. The derived hydrogen production costs are highly sensitive to the assumed discount rates, which are influenced by various risk factors, including economic and natural hazard risks, differing between regions. To ensure more accurate cost assessments, it is recommended that these rates be specified on a country basis. In addition, given the potential role of the existing gas transmission network for hydrogen transport, its impact on transport costs should be included in future evaluations.

ACKNOWLEDGMENT

The conducted work is part of the ELYAS project (03EI1053) that is funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK). The development of the ETHOS model suite was also supported by the Helmholtz Association under the "Energy System Design (ESD)" program.

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